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Managing electric power system transition in China

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ABSTRACT

This research studies the low carbon transition of the electric power sector in China using a multi-level perspective (MLP) of niches, socio-technical regime, and landscape, as well as literature on innovation systems. Three lines of thought on transition process are integrated in the paper to probe the possible transition pathways in China. A MLP analysis is presented to understand the current niches, regime, and landscape of China's power sector. A brief analysis on the future macroscopic socio-economic transition in the process of industrialization, urbanization, and modernization of Chinese society and its implication on power landscape are depicted to prove the urgency and magnitude of transition in China and why systematic transition management is needed. Five transition pathways, namely reproduction, transformation, substitution, reconfiguration, de-alignment/re-alignment, and reconfiguration, with their possible technology options are presented. The paper goes further to propose an interactive framework for managing the transition to a low carbon energy system in China. Representative technology options are appraised by employing innovation theory to indicate the logic of policymaking within the framework. Institutional gaps in realizing the transition are also addressed. The work presented in the paper will be useful in informing policy-makers and other stakeholders and may provide references for power sector transition management in other countries.

Contents

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1. Introduction

Under the background of global transition to a low carbon economy, energy system in China has recently aroused fervent attention. The literature addressing low carbon energy development in China recently can be classified into two main lines, policy study [1–9,amongothers] and modeling/scenario study [10–16,amongothers]. The focus of policy research is on the potential of various low carbon options and the appropriate policies to facilitate their deployment. On the other side, the emphasis of modeling/scenario study is on the structure and logic of the underlying models and all possible low carbon pathways, without much concern on how these low carbon niches can develop into the mainstream of the energy system. With these efforts, different versions of a sustainable energy future for China are portrayed and viable policies are recommended, thus adding to our understanding of energy issue for China, the largest energy consumer and GHG emitter, as well as the most populous developing country in the world. While modeling/scenario study mainly deals with "where to go" and policy study deals with "what to do", there is still a gap between them, that is "why and how to do". Particularly, transition from a heavily coal-dependent economy to a low carbon one with significant improvements in energy efficiency under globalization, industrialization, and urbanization in China is tremendously difficult. A lot of interlocked factors such as economic structure, urbanization, and transportation system, should be proactively managed.

Though energy transition has been extensively studied recently, the magnitude and complexity of the challenge have not yet been widely recognized. As noted by Larsson [17, p. 1], "*The transformation of existing energy systems to sustainable and renewable alternatives represents a tremendous management challenge. We need to view it as an opportunity to renew energy systems and renew important parts of the economy and social life … So far, primarily the technical aspects of different alternatives have been debated. We know a lot about 'what' has to change. So far, however, very little has been written about the 'how' of the change process*".

Recently there are a few authors employing a multi-level perspective (MLP) framework in a combination of technical, social and historical analysis, sometimes elaborated by system innovation and co-evolutionary viewpoints in energy research literature [18–29]. While some of the authors have addressed specific cases for developed countries like the UK and the Netherlands [22,24–25] and some general cases for developing countries [30], others have addressed the history and general trends of the energy systems [31,32]. In this research, the following questions are of particular interests: "What is the character of the particular socio-technical landscape that shapes the energy system in one country?"; "What are the main challenges under sustainability transition?"; "How can the potential improvements within the current technical regime and the novel niches begin to break the current regime?"; "What is the proper policy (if any) that can facilitate the transition?". By focusing on these issues, these researchers provide a promising new direction for energy system transition study.

China is in a process of rapid industrialization, urbanization and modernization, which distinguishes itself with its industrialized counterparts. A variety of macroscopic factors will exert implicit or explicit impacts on energy system transformations. In this sense MLP is an appropriate methodology for addressing China's energy system transition. This research is such an attempt to employ this new method to study China's power systems transition. It is worth noticing that, as a field far from being maturity, there is an ongoing fiery dispute on whether purposeful governance for sustainable development and deliberate policy aiming to transform regimes is possible [26]. Leaving aside the theoretical dispute, we insist that a well designed set of vision, policy and plans will fare better for delivering sustainable transition.

The layout of the paper is as follows: the Methodology section introduces the methodology for the study; the Current power landscape and niche in China section discusses the current landscape of the power sector in China and the niche technology options for the low carbon transition; the Pathways towards low carbon power system in China section discusses the possible pathways for transition and the underlying challenges; the Policy design implications for transition management section discusses the management framework for transition; and the Concluding remarks section is the concluding remarks.

2. Methodology

2.1. Multi-level perspective for socio-technical transition

In seeking to develop transition pathways for China's power sector, strongly encouraged by call for an organized plan for energy transition [17,24], we are motivated by the desire from stakeholders for conceptual frameworks that enable the examination of plausible future pathways to inform decision-making. Actors are increasingly driven by the need of keeping the economy growing while reducing carbon emissions. This implies radical and disruptive changes to be achieved while maintaining 'secure' energy supplies and meeting 'reasonable' energy service demands at 'affordable' costs. Previous work largely focuses on technically plausible futures and their likely costs and benefits, often using modeling approaches that assume a high level of economic rationality of the actors. Despite its useful insights, such work does not illuminate how technological changes arise through the dynamic interactions between a range of actors with different perspectives and goals. Their decisions and behavior are likely to be key influences on how to get from 'here' to a radically different low carbon 'there'—and need to be understood if effective policy strategies and instruments are to be developed. Our starting point is that frameworks developed to examine past system transitions and guide the management of future transitions could usefully be applied to understanding the changing roles, influences and opportunities of actors, both large and small, in the dynamics of future energy transitions.

Our approach is built on the multi-level perspective (MLP) for analyzing the dynamics of transitions, developed primarily by Dutch researchers [18–21]. This method combines technical, social and historical analysis and insights into past and current transitions, using an analytical framework based on interactions among three levels: technological niches, socio-technical regimes, and landscapes. In particular, landscape represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society and only change slowly. The socio-technical regime reflects the prevailing set of routines or practices that 'actors' and institutions use and that create and reinforce a particular technological system, including "engineering practices; production process technologies; product characteristics, skills and

procedures [...] embedded in institutions and infrastructures" [18]. Whereas the existing regime generates incremental innovation, radical innovations are generated in niches, which are spaces that are at least partially insulated from 'normal' market selection in the regime, for example, specialized sectors or market locations. Niches provide places for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user–producer relationships. Transition pathways arise through the dynamic interaction of technological and social factors at and between these different levels.

The transitions study approach has developed along three main lines, namely historical description, transition management, and scenario development. In the first line, developed mainly by the Dutch researchers, the MLP is used to provide a framework for explaining historical dynamics. For example, [22] analyzes the historical dynamics within the Dutch electricity system from 1960 to 2004. Ref. [23] analyzes the changes that have taken place in the UK's energy system over the past several decades. The second line is interested in the creation of a 'transition arena' for a relatively small group of innovation-oriented stakeholders to engage in social learning about future possibilities and opportunities. The third is interested in creating a scenario which can explores potential links between various options and analyzed how these developments affect and are affected by the strategies (including policies) and behavior of various stakeholders [27] (see [26] for more details). Similar to [24], our theoretical approach to developing transition pathways is an elaboration of the socio-technical scenarios method, augmented by recent thinking in innovation systems research. The theoretical basis for linking these different methodologies, which builds on the work of [28] and further elaborated by [26], is described briefly in the next section (see [29] for more details). In a similar fashion, Mitchell [33] also highlights the importance of the regulatory paradigm and the wider socio-political landscapes and their impact on delivering energy system change, emphasizing the influence of a regulatory state paradigm (similar to landscape in MLP literature) and policies regulating stakeholder behaviors.

2.2. Transition pathway

Regarding transition pathway, different authors have proposed different topology depending on whether they believe transition is manageable or not. In the school of Transition Management, [34] understands regime change to be a function of two processes: (1) shifting selection pressures on the regime, (2) the coordination of resources available inside and outside the regime to adapt to these pressures. Selection pressures consist of economic pressures (competition, taxes, charges, and regulations), broad political, social and economic 'landscape' developments, and pressures that "*bubble up from innovative niches that are not yet so established as to constitute a regime*". In their understanding "*without at least some form of internal or external pressure in the diverse senses discussed above*, *it is unlikely that substantive change to the developmental trajectory of the regime will result*". For adaptation they distinguish two dimensions: (1) availability of resources (factor endowments, capabilities, knowledge) and (2) degree of coordination of resource deployment. Assuming that selection pressures are always present, [34,35] combine the two adaptation dimensions to construct a typology of four transitions.

According to [35], 'endogenous renewal' results from regime actors making conscious and planned efforts in response to perceived pressures, using regime-internal resources. 'Reorientation of trajectories' results from a shock either inside or outside the incumbent regime, followed by a response from regime actors using internal resources. 'Emergent transformation' arises from uncoordinated pressures, outside the regime, often driven by small and new firms. 'Purposive transitions' are intended and coordinated change processes that emerge from outside the existing regime. Purposive transitions are seen as "deliberately intended and pursued from the outset to reflect an explicit set of societal expectations or interests".

Another line also in the school of Transition Management, inspired by Cultural Theory [36], argues that there are three experiencable patterns of social relationships: ego-focused networks, egalitarian bounded groups, and hierarchically nested groups. There are two further experiencable positions: involuntary exclusion from all these organized patterns (fatalism, with imposed relations) and voluntary withdrawal (the hermit). The overall picture is a five-fold, self-organizing system. Accordingly, [37] proposes the transition topology as: egalitarian, individualist, hierarchist, and fatalist. Ref. [37] further argues that "*in the initial stages the egalitarian or fatalist approach may be most appropriate*, *the individualist and maybe hierarchic modes might be the most relevant ones in a later stage of the change process*", because "*in the end actors in the system should work in line with the new desired setting*, *either as a result of market incentives* (*individualist mode*), *or institutional and other settings* (*hierarchist mode*)". It seems that their analysis finally resides to the dichotomy of market and managed planning, as if they were totally opposite. As for us, vision, strategy and planning are of vital importance for energy system transition, but it does not necessarily exclude the role of market mechanism [17,33]. Hence in the following section, we adhere to the combination of market incentive and planning for the power system transition in China.

In the school of Innovation Transition, [38] refutes [35] and insists that no transition is planned and coordinated from the outset and every transition becomes coordinated at some point through the alignment of visions and activities of different groups. To counter the presumed, bottom-up, niche-driven bias in the understanding of transitions, and highlight the timing and nature of interactions, [38] proposes the typology of transition as five types as: (1) reproduction: on-going processes of change within the socio-technical regime (i.e., not involving interaction with the landscape or a technological niche); (2) transformation: processes of change that arise from the interaction of an evolving landscape with the socio-technical regime (but not with the technological niche level); (3) substitution: replacement of one dominant technology within the socio-technical regime by another as a consequence of interaction between all three levels; (4) de-alignment/re-alignment: interaction between the three levels resulting in competition between a dominant technology within the regime and a number of other competing options, which have different performance characteristics, eventually resolved through emergence of a new dominant option; and (5) re-configuration: replacement of a set of interlocking technologies by an alternative array of inter-related technologies which fulfill the same, or similar functions.

2.3. Our approach

As noted by [37], a specific blueprint for governance of system innovations is not a wise course of action currently. More fundamentally, modern insights from sociology and the philosophy of science make it doubtful if one can ever obtain convincing proof that one well thought-out governance theory is scientifically superior to another. With a pragmatic viewpoint, we employ a hybrid strategy taking into account the above-mentioned transition pathways. The perspective by [38] will be employed for transition pathway study. In addition, we will identify pathways combining both market and planning tools to try to be proactive and avoid the deadlock of unwanted emergent transformation by 'purely endogenous interactions under market mechanism.'

In specifying plausible transition pathways for the future development of China's power systems, we focus on different

pathways for the governance of these systems and their implications for the rates of innovation and technological developments needed. Then based upon innovation theory, the barriers for the transitions are analyzed according to technology launch path. Because our motivation is not to appraise the technology and recommend policy on a case-by-case base, we propose an interactive framework for transition management on methodological perspective and only appraise representative technologies in detail as case studies to show how to design a consistent package of policies for the low carbon transition.

3. Current power landscape and niche in China

3.1. Brief history of power systems development in China

China stepped into the era of the electric lamp as early as 1879; but the current power system is developed from scratch ever since the birth of People's Republic of China in 1949. As summarized by [39,40], the history of China's power system can be divided into four periods. From 1949 to the middle of 1980s, in a centrally planned and administrated system, the power sector was run by a State-Owned Enterprise (SOE), which was also a ministry affiliated with the State Council in the central government. Its branches were administration bureau which were affiliated to local governments at all levels. Because of continuously increasing demand, power supply was never able to meet the demand. Thus strict rationing of power supply for factories and blackouts in urban areas was common. In most rural areas, there was no access to electricity at all. During this time, the shock of Oil Crises of the early 1970s caused deep worry about the security of fuel in developed countries, which resulted in the first round of nuclear power boom. However, because of the historical mistrust between the East and the West, nuclear power generation was unavailable in China until the 1990s.

During the period from 1985 to 1997, to cope with serious power shortage, the central government introduced the decentralization of power sector to the provincial governments and opened the investment of power generation to provincial governments, private and foreign investors with guaranteed returns. Meanwhile, the ownership and operation of coal mines was also decentralized to the provincial governments and opened up to private investors to gradually secure coal supply at a relatively low price. The decentralization of investment decisions and the relative low fuel price have spurred the rapid growth of coal-based thermal power plants and large-scale hydropower plants construction. During this period, there was boom in gas turbine power plants construction in industrialized countries due to oil price collapse in 1986 and the discovery of large oil fields around the world. However, due to a poor endowment of oil and gas, gas power did not enter into the generation mix in China.

During 1997–2002, with the macroscopic reform of government functions, in power sector there was a separation of government and business operation and the creation of State Power Corporation (SPC). During this period, the relationship between SPC and provincial power corporations suffered continuous conflicts. Since 1998, the State Council declared to accelerate the construction and refurbishment of rural power systems to increase electricity access in rural areas. Because of the 1997 Asian Financial Crisis and the vast investment in power facility, the headache of power shortage was largely eased during this period.

In 2002, as a response to worldwide deregulation of the power sector and continuous conflicts in the existing management framework, the central government introduced the unbundling of generators and grid companies. Five national generators and two grid companies were established. These five national generators, two grid companies, together with dozens of provincial generators comprise the incumbent of China's power sector. State Electricity Regulatory Committee (SERC), the power regulator in China, was also created, though its independence and mandate capacity still need to be enhanced. With reforms, the principle of incentive-based operation is gradually introduced in the power generation sector. Since 2002, with the recovery of China's economy from the 1997 Asian Financial Crisis, power demand increased quickly and the installation of new power generation capacity is extraordinarily spectacular. In 2007, China's power system could manage to provide proper supply without large-scale blackouts [40, p. 58] Fig. 1.

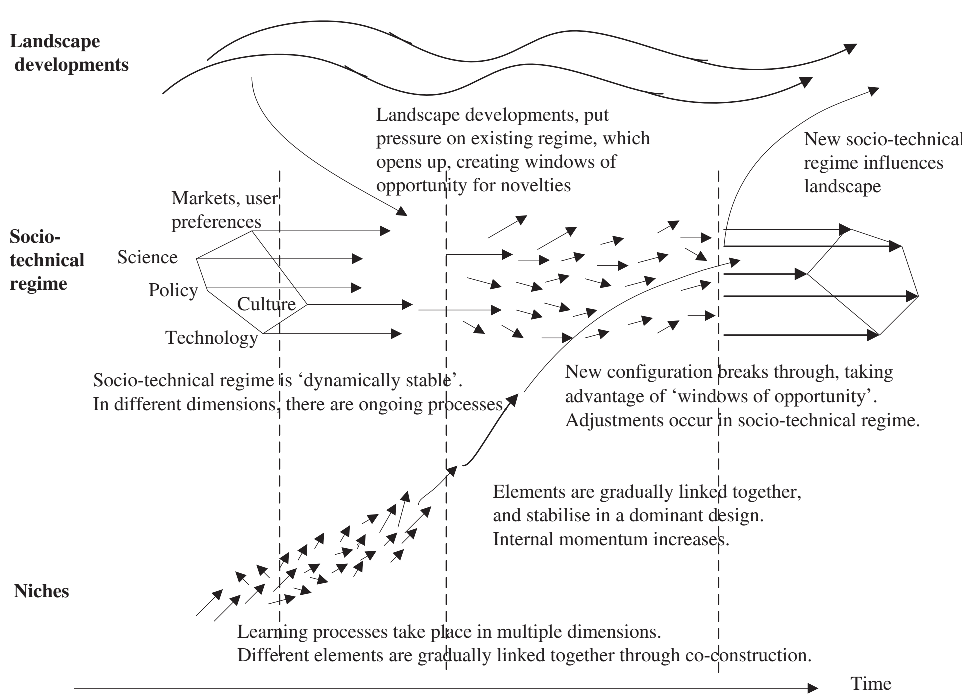


Fig. 1. Multi-level perspective framework for socio-technical transition study [19].

3.2. Overall picture of China's power systems

Growth of electric power consumption has occurred faster than that of primary energy consumption over the past three decades and has resulted in tremendous growth of power generation capacity and rapid electrification (Fig. 2). From 1980 to 2009, annual electricity demand in China grew more than 12-fold, from 300 to 3660 TW h [41]. Demand growth of this magnitude and speed has contributed to consistent and severe capacity shortages. At the same time, generation capacity in China has increased significantly to meet with the power demand. In 1980 the total generation capacity in China was only 65.8 GW, while in 2009 the installed capacity amounted to 863.6 GW, also a 12-fold growth (Fig. 3). Especially after 2004, the annual net increase in generation capacity always ranges between 50 and 100 GW, thereby creating a new record in the history of world power system. Only the United States once maintained the annual growth of 50 GW during the 1970s. With the rapid development of power systems, the enhancement in grid infrastructure and operation brought about the decrease in line (transmission and distribution) losses. In 2005, China's power line loss was 7.12%, ranking the upper middle level compared with other countries [42].

The coal-based generation mix results the carbon lock-in in China's power system, making it the largest contributor of CO_2 emissions in China as well as the main source of other environmental pollution. China's primary fuel mix is dominated by coal, a factor that determines China's significant environmental pollution [43]. According to estimates by various experts, the coal reserve could be exploited for more than 100 years under the current production and consumption rates, while the remaining proven recoverable reserves of crude oil and natural gas could be exploited for only 20 years and 37 years, respectively [44].

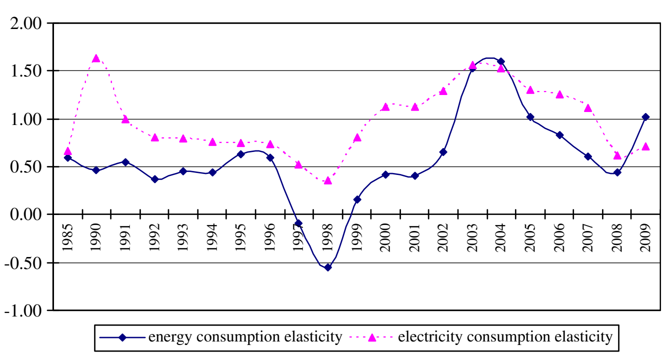


Fig. 2. Energy and electricity consumption elasticity in China, 1985–2009 [41].

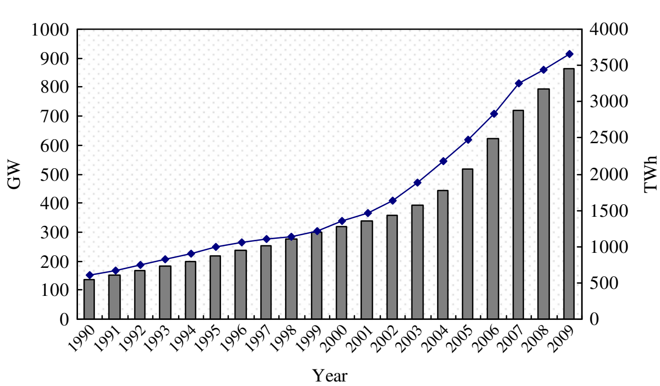


Fig. 3. Total generation capacity and electricity consumption in China, 1980–2009 [41].

The exploration of gas reserves in recently years has made encouraging progress and may significantly expand its exploitable years [45, p. 128], which provides the possibility for gas power development in China. This situation has determined China's coal-based energy consumption structure (Fig. 4), which has further led to China's generation mix being dominated by thermal power units. The share of thermal power units in the entire portfolio was as high as 70%. As a result, the thermal power units consumed more than 50% of the country's total coal resources in 2007 for meeting most of the electric demand in China (Fig. 5).

Because of the heavy reliance on coal, CO_2 emissions from power generation in China are significantly higher than the world average and of most countries in the world. In 2007, CO_2 emissions per kW h electricity generation in China were 758 g, comparing to 507 (world average), 549 (the United States), and 362 (European Union's 27 nations). In 2007 China emitted 6007 million tones (Mt) CO_2 while the power sector alone contributed about 2700 Mt from coal combustion, or around 45% of total emissions [48]. The power industry was also the largest emitter of other primary pollutants, responsible for 45.2% and 45.39% of the country's total SO_2 emissions and particulate emissions in 2008, respectively [46].

Although China's generation mix has been relatively stable over the past two decades, the composition of coal-fired power plants has undergone a significant shift toward larger and more efficient units. In the 1990s, most of the thermal units above 300 MW installed in China were imported. In 1993 the share of units 300 MW and accounted only for 23% of the total thermal generating capacity. In 2007, the share of 300 MW units and above and 600 MW units and above accounted for 50% and 21.6% of total thermal generating capacity, respectively. At the end of

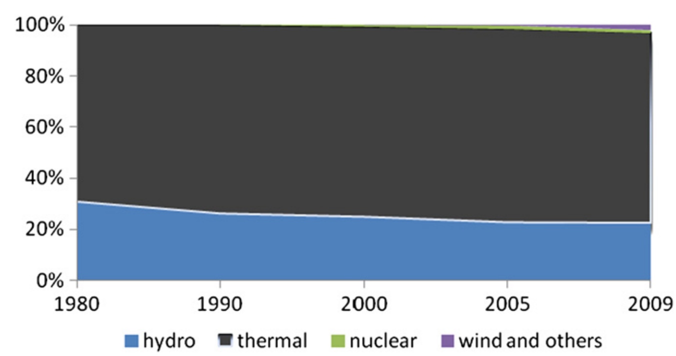


Fig. 4. China's generation mix [46].

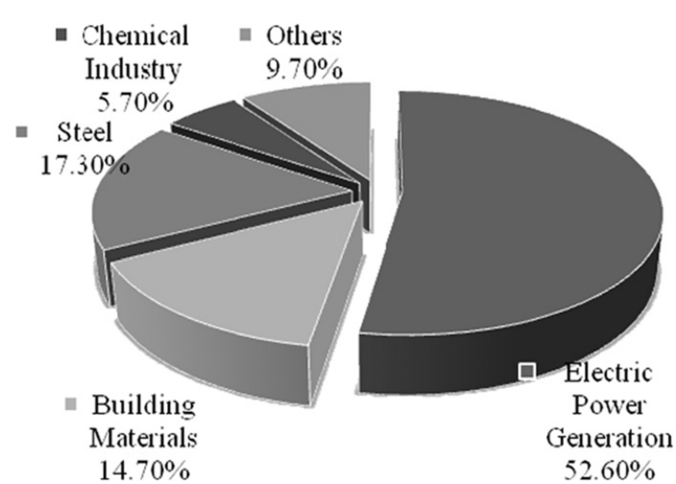


Fig. 5. China's Coal Consumption Structure in 2007 [47].

2009, the shares of 300 MW units and above rose to 69% [49]. In addition, at the end of 2008, there were 10 units of 1000 MW ultra supercritical (USC) generators in operation. Meanwhile to raise the energy efficiency in power generation sector, China's central government have led an effort to shut down small ($\leq$ 50 MW) and old ($>$ 20 years, $\leq$ 200 MW) units, retiring 72.1 GW of these units between 2006 and 2010 [49]. As a result of this push toward higher generation efficiency, the average thermal efficiency of coal-fired power plants in China has sustained a linearly increasing trend since the 1990s, and now reportedly surpasses the average efficiency of the U.S. coal plants by a significant margin. In 2007, CO_2 emissions per kW h electricity generation in coal-based thermal plant in China were 893 g (down by 7% from 1992 level), lower than the world average (903 g), the U.S. average (920 g) and Japanese average (910 g), but still higher than European Union 27 nations average (835 g) [48].

The imbalance between power load and power resource necessitates long-distance large scale power transmission in China. China's power grid is divided into four regional synchronous grids. The Northeast-North-Central, East, and Northwest regions operated by the State Grid Corporation, while the South operated by the China Southern Power Grid. Although basic DC interconnection among regional grids was achieved in 2005 [50], power flow among regions and even between provinces within regions remains limited.

Meanwhile China has large spatial disparities between energy resources and load centers, and between regions with coal, hydropower, and wind resources. Coal reserves are concentrated in the north, load centers along the eastern seaboard, wind resources in the Northeast and North grids, and hydropower in the Central and South grids. The lack of greater interconnection among regional and sub-regional grids imposes constraints on optimal use and delivery of energy resources, limiting the availability of dispatchable hydropower resources to provide peaking and ancillary services and straining the transportation system because of the vast need to ship coal by rail and road.

Operation efficiency, especially in an environmental sense is notoriously low because of the guaranteed return policy since the 1990s. Dispatch in the Chinese power sector has, since the early 1980s, operated under an "equal shares" formula whereby generators of a given type are guaranteed a roughly equal number of operating hours to ensure adequate revenues to recover their fixed costs. Economically and environmentally, this practice is inefficient, as generating units with higher heat rates (i.e., lower efficiency) may receive the same number of operating hours as those with lower heat rates. In addition, equal shares dispatch has contributed to inefficient generation investment by encouraging overcapacity [51]. Average capacity factors for coal-fired generators were only 55% in 2009 [41]. However, the root of the inefficient dispatch rule originated from the incentive policy of guaranteed investment return on generation during the 1990s. Because power plants usually have operation life-cycles of 30–40 years, reformation to a more efficient rule has proven difficult. Five provinces began to experiment with an energy efficient dispatch system in 2007, but this pilot system has met with technical and economic obstacles and has not been replicated in other provinces [52].

Many of the generation services provided by natural gas units in other countries are instead provided by coal or hydropower units in China. In regions that do not have hydropower resources, coal units are used for load-following and peaking generation, requiring significant cycling of coal units and reducing the efficiency of these units. Coal plants are also often used to provide the ancillary services required to maintain grid reliability, including spinning and non-spinning reserves.

Without a formal and transparent pricing mechanism that can link real cost and retail price, the current pricing policy poses significant barriers to transition to a more efficient power system. Despite incremental changes to wholesale generation and retail rates, China continues to lack a formal, transparent mechanism for linking costs and retail prices in its electricity sector. Wholesale generation rates in China have historically been loosely based on average costs. Since 2004, rates for thermal generators have been set using benchmark pricing, in which generators in the same technology class are given the same tariff, based on an estimate of annual output and fixed and variable costs for that class. As coal prices rose in the 2000s, China's central government developed a "co-movement" mechanism that allows for some pass through of fuel cost increases. Wholesale rates for renewable generators are set using regional benchmark prices, while rates for hydropower and nuclear generators are set on a facility-by-facility basis because of the vast initial capital investment cost of these generators. Provision of ancillary services has historically been limited in scale and scope, mandatory and uncompensated, but plans to compensate generators for services are currently in the early stages of implementation. Because of the dominance of coal in China's electricity system, this predominantly benchmark-based approach to wholesale pricing means that generation supply curves in China tend to be relatively flat.

The revenues grid companies receive for transmission and distribution (T&D) services are currently based on the residual between retail sales and generation costs. This residual is inherited from historical prices and is not based on a bottom-up accounting of T&D costs. Beginning in 2005, the State Electricity Regulatory Commission (SERC) developed accounting standards and reporting requirements for grid companies, but the level of detail and transparency in the disclosures required by SERC is not sufficient to assess whether costs are reasonable [53]. Moving toward cost-based T&D pricing is a continuing priority for regulators [54].

Retail electricity prices in China have historically been designed to reflect government policy and social priorities (e.g., maintaining low fuel prices to boost economic growth and affordable fuel prices for household), instead of the cost of service [40]. Commercial customers and, to a lesser extent, other industrial customers pay at higher electricity rates that subsidize agricultural users, fertilizer producers, large industrial customers, and residential customers. There have been some adjustments to the retail pricing system to deal with emerging challenges. Since the 1990s, many provinces have begun to use retail pricing to manage peak demand, with both interruptible and time-of-use (TOU) pricing for industrial, commercial, and, in a limited number of provinces, residential customers. To encourage conservation, China's central government is currently drafting rules to create step tariff rates for residential customers. Neither TOU prices nor step rates are ultimately cost-based. The lack of a cost basis can lead to perverse incentives, such as encouraging grid companies to sell more power in peak periods under TOU rates [54], which is the natural behavior of a monopolist.

Developing renewable energy in power systems is still troublesome with difficulties. China has a rich endowment of renewable energy and has formulated favorable policy for renewable energy development. Given the relatively high costs for solar and biomass power, wind is and will likely continue to be the principal non-hydro renewable resource in China. Ever since the publication of *the Renewable Energy Law* formulated in 2005 and the *Medium-and-long Term Development Planning for Renewable Energy* in 2007, wind power has experienced rapid growth in China [55,56]. At the end of 2010, installed capacity connected to the power grid has increased from 1.06 GW in 2005 to 31.07 GW.

Wind power is initially taken by the Chinese government as a means for solving the problem of electricity access of village residents and herdsman in remote areas and thus a niche market was initiated. Its recent successful penetration into the power regime depends on the interactions of the following factors: (1)

the issue of *the Renewable Energy Law* and related planning has provided a positive signal and stable expectations for investors; (2) most importantly, the government's stipulation on the renewable generation portfolio for major generators has made it a necessity for them to develop wind power projects when getting new thermal power plants approved by the government; (3) the favorable price subsidy policy and availability of CDM for project support by the carbon trade has spurred the enthusiasm of investors; and (4) global development and the growth of domestic manufacturing has decreased the investment cost to make wind power more attractive to investors.

Although China's wind power growth has been the most spectacular in the world for the past decade, the following factors have posed and will pose serious threats to its sustainability. First of all, because of the intermittence of wind power generation, the grid companies in China are reluctant to integrate it into the power grid. Even though the renewable energy law stipulates the obligation of the power grid to purchase the full amount of renewable generation accessed to the grid, without specific operation rules, grid operators simply reject wind power access with reasons such as unpromising access conditions, operation safety requirements, etc. The wind capacity factor was as low as 23.7% in 2009, which is the evidence of the difficulties of wind access [41]. Second, the incompatibility between wind power projects and the power grid expansion planning has made grid access difficult. China has formulated ambitious planning of eight large-scale inland windmill bases in 10 GW scale in the provinces of Xinjiang, Inner Mongolia, Hebei, Jilin, and Shandong. However without synchronous power grid expansion and proper reserve capacity plants, it is unlikely that this plan can be realized. The recent experience of the Western Inner Mongolia Power Grid is such an example at hand [41]. Third, the current policy to develop wind power is unsustainable because it neglects the vast investment requirement in the power grid and discriminates against small projects and small investors. The bidding rule is bundling the regional wind resources together into projects in scale of GW and choosing the bidder with the lowest price. The policy is effective in project development and cost reduction. The equipment cost has been successfully cut down from 6000 RMB/kW in 2004 to around 4000 RMB/kW in 2010. However, it simply leaves the issue of grid connection to the grid operator and finally leaves it unresolved. There is no surprise that under such policy most of the wind projects are operated by the five big national SOE generators and other large province-owned generators, which is different with the success of wind power in Germany and the Netherlands where various small investors enter into the wind power market. Considering the long-term wind power development prospective, an optimal development of wind power should consider the solutions of both a "large windmill base and long-distance transmission" and "distributed power generation", which in turn call for the entrance of small investors into wind power market. However, under the current policy, the opportunity for small investors with limited finance resources is almost impossible. Finally and perhaps the most importantly, the current price mechanism for wind power is also problematic. The lowest price bidder mechanism and the low capacity factor have resulted in the unprofitability for investors and it discourages the confidence of the generators. On the other hand, there are still no concrete stipulations addressing the issues of grid cost recovery for additional transmission investments and more reserve capacity when incorporating wind power into the grid.

3.3. MLP analysis of power system in China

3.3.1. Power landscape and regime in China

The current power system regime in China for meeting industrial process, lighting, heating and power-related services may be characterized as a centralized system. Electricity is centrally generated, largely from coal, hydropower, and a small but growing amount of nuclear and renewable sources; it is delivered to businesses and homes through the large scale transmission and distribution networks, before being used to provide power, lighting, heating and services with the aid of end-use technologies and the buildings infrastructure. The absolute low starting point, the vast growth in power demand incurred by rapid industrialization of the Chinese economy and the rise of China as a world factory, as well as the increasing demand from household as a result of enhanced living standards and the popularization of home appliances, make rapid growth of the power supply capability a policy priority in China. The strategic importance of energy to enabling economic activity and well-being means that the system is the subject of intense policy activity, which focuses on ensuring secure and affordable supplies, and other social objectives. The meta "socio-technical landscape" of electric sector in China can be characterized as:

- a dependency upon fossil-fuel-based energy supply (mainly coal and rising supply capability of gas) and large-scale electricity generation technologies,
- a coal extraction, importing, processing and transportation infrastructure always unable to catch up with increasing demand,
- province-based power grids and a growing interconnected national grid to ease the geographic imbalance between supply and demand,
- historically vertical integration monopoly just being restructured into two grid operators and a sets of SOE generators who are regulated by government bodies,
- a weak but expanding rail and road infrastructure,
- a traditionally centralized administration system, while power market reform initiated but rather fruitless.

It is worth noting that the province-based power system, are largely a result of the decentralization of power system to provincial policy during the 1985–1997 period, and that was one of the reform priorities in 2002. In the reform program of 2002, when dismantling SPC, two grid companies, China Southern Power Grid (CSG) and State Grid (SGCC) were established. CSG, managing the power grid in five provinces, Guangdong, Guangxi, Guizhou, Yunnan and Hainan, is the result of experimentation on regional power grid management for optimization of power resources in larger areas, while five regional power grid corporations affiliated to SGCC (managing the power grid in the rest of the provinces except for Tibet and Western Inner Mongolia) were also established. However, trying to maintain its power SGCC has deprived the designed functions of the affiliated regional power grid companies. Though in the 2002 reform program, paragraphs like 'promote regional electric market reform in appropriate time' was included, but so far no policy has ever since addressed this issue. Another leading reform goal "to break the monopoly and introduce competition" also came to a deadlock. The entrance of private or foreign investors into power generation market is still limited. SOEs (including central and local governments) enjoy monopoly power on generation side and control 90% of generation assets [57]. Introduction of competition on the generation side was preliminarily experimented within Northeastern China but soon stopped because of consistent power shortages since 2002. Retail price is still strictly regulated by the government and customers (including industry and commerce customers) do not have the right to choose suppliers.

The 'landscape' provides the dominant assumptions, values and deeply rooted socio-economic trends at a given period of time. It also encapsulates the key 'philosophy' behind policy-making trends and in that sense can be said to reflect the dominant perception of 'problems' and the ways to resolve those

problems in electricity sector. In China key processes that influence or 'drive' the power regime at the landscape level include:

– the increasing power demand from the industrial sector because of the on-going industrialization process and a big gap in energy efficiency compared with the rest of the world,
– the increasing power demand from households because of increasing income and rapid urbanization,
– a huge population base of 1340 million and still growing,
– the increasing pressure on primary energy supply, environment and ecology because of the heavy reliance on coal,
– global concern of GHG reductions and increasing pressure on China's "measurable, reportable and verifiable " obligation to cut GHG emissions,
– China Government's commitments to reduce emissions, and reduce GDP carbon intensity by 40–45% in 2020 as of 2005 and to promote clean energy sources, increasing the share of non-fossil over primary energy by 15% in 2020,
– concerns over security of primary energy supplies,
– external factors leading to high and/or volatile oil and gas prices and related concerns over energy affordability and fuel poverty, as well as physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc),
– the gradual transition of the Chinese economy from centralized planning to a more market based economy that will gradually blend into the global economic system,
– the international efforts to deliver renewable energy technologies.

Many processes that drive the power landscape in China, such as energy security concern and international factors are the same as other countries face. However, under the macro-economic-social transition process, the interactions of industrialization, urbanization, and energy-environment-ecology constraints, will pose important impacts on the power landscape, and thus influence the transition pathways. We will address these issues at the end of this section. Meanwhile, the international pressure on China to assume "measurable, reportable and verifiable" CO_2 reduction targets will intensify during China's growth process. Currently, by emphasizing that as a developing country and according to "shared but differentiated" principle, China can and will take active measures to cut CO_2 emissions so far as they do not impede the economic development. As expected in 2020, per capita GDP of China will exceed 4000 US$ and in 2030 it is expected to exceed 7000 US$ (2000 constant prices). It is highly likely that in 2015 when per capita GDP will exceed 3000 US$ China will step into the upper middle income country group according to the World Bank standard [58]. At that time, with its raised share of global GHG emissions and the expected intensified international conflicts, it is very likely that Chinese Government would need to take a more positive attitude toward GHG reductions. Thus in the future 5–10 years, the landscape for power sector will definitely experience radical change towards decarbonisation and therefore exert more pressure the power regime to change.

3.3.2. Technology niches

A wide range of competing energy technologies are currently being developed, reflecting not only the underlying scientific and technological base but also the perceived opportunities arising from the emerging low-carbon socio-technical regime. Ref. [23] has proposed a categorization of these technologies, distinguishing between mature technologies and those that are at various stages of commercialization, demonstration, research and development. Ref. [59] also appraises the renewable energy technology progress in China and proposed their categorization. However, their categorizations mainly focus on pure technological level and neglect final consumption as a means for efficiency improvement by technological innovation in the industrial process. Based on their work and adapted to our pathway study purpose, we propose our decarbonisation categorization for power sector transition in China (Table 1). In our categorization, we classify available and potential options into five streams, namely fossil-fuel, nuclear, renewable, demand-side and energy carriers and storage technology and appraise the availability of options into typical technology innovation stages: mature, being available at hand with affordable prices in large scale; early commercialization, though technically feasible but still being expensive and in need of technological learning process to become technically effective; development and demonstration; and the research stage. The time line in the table is not strict, given the uncertainty

Table 1
Niche energy technology options analysis.

Stage of (technology) option	Fossil-fuel based	Nuclear	Renewables	Demand-side technologies	Energy carriers and storage technologies
Mature	USC boilers combined heat and power generation (CHP)	Existing fission reactors	Wind turbines traditional geothermal technology	Energy-efficient appliances compact fluorescent light Industrial process innovation	Batteries
	Gas (coal bed gas) power generation		solar heat water system biomass generation Hydropower	House insulation Heat pump (geothermal or air)	Pump storage
Early commercialization (6–15 years)	Some gasification technologies some CO_2 capture technologies CO_2 storage (CCS) retrofitting of old boilers to USC	New fission reactors	Some wind turbines Biomass boilers biofuels PV and CSP Grid modification	Passive solar low-carbon buildings LED lighting system	Fuel cells
Development and demonstration (D&D) stage (15–20 years)	Some CCS technologies integrated gasification combined cycle (IGCC) underground coal gasification polygeneration Fischer–Tropsch process	Fourth generation reactors (high temperature gas reactors etc.)	Wave Tidal biofuels, e.g., gasification, AD, transport fuels Grid modification	Intelligent buildings smart meter The internet of things	Hydrogen from gas and electrolysis Fuel cells
Research stage (20 years and beyond)	Novel CO_2 capture technologies	Nuclear fusion	Biofuels e.g., pyrolysis enhanced geothermal system New materials for PV		Hydrogen generation from biomass, waste, nuclear, etc.

Source: compiled by authors based on [17,24,59–61].

in innovation and the inaccuracy of appraisal, and is calibrated based on technology launch (development, introduction and deployment of new technology into widespread use) stage.

As we can see from Table 1, on the fossil fuel stream, though in the long-term CCS and IGCC technology is highly promising and thus will provide opportunities for coal remaining in the generation mix, in the near future (less than 10 years), large-scale commercialization of these technology is unlikely and the most reliable options are to rely on USC and CHP to increase the energy efficiency of newly built thermal power plants. On the other hand, with the recent inspiring progress on natural gas exploration and the technology advance in coal bed gas recovery, gas plants for peak load and/or cogeneration have a very promising future. Considering the lower CO_2 emission factor of gas as of coal, this is helpful for alleviation of carbon emissions.

On the renewable energy stream, hydropower is still expected to take the lead for at least the next decade, because of its low cost and operational superiority. Wind power is the most promising renewable technology besides hydropower. The domestic manufacturing of wind turbines has made significant progress ever since 2002. Currently the mainstream unit is in 1.5–3 MW and the price decreased to around 4000 RMB¥/kW in the end of 2010 (comparable or less than thermal power unit price). Meanwhile the benchmark price for wind power set by NDRC in 2009 ranging between 0.51 and 0.61 RMB¥/kW h is already lower or approaching peak hour retail power price in some areas. In the end of 2010, domestic manufacturer SINOVEL produced China's first 5 MW turbine unit and it is expected to release the 6 MW unit soon. Another domestic manufacturer XIANGJIANG GOLDWIND also plans to accelerate the research and development of a 6 MW turbine. When the 5 MW and above units enter the large-scale commercialization stage, the technical economics of wind will make the large-scale offshore wind projects feasible. Solar power in China has also entered the early commercialization stage. Some demonstration projects are deployed but power generation price is still high. Currently unit investment for PV in China is around 12,000–14,000 RMB ¥/kW and generation cost ranges between 0.9 and 1.1 RMB ¥/kW h. This cost level is similar to wind power in 2002 and if the successful experience could be copied, solar power would enjoy rapid growth in the coming decade. Biomass generation technology has also matured in China. However, because of the limited supply of energy crops and because of direct competition with other sectors such as agriculture and husbandry, the scale of biomass generation is tiny in only about 1 GW and is thus difficult to become part of the main power regime. On the other hand, the development of small-and medium-scale distributed biogas or waste generation in rural or urban areas is promising. Globally, other renewable generation technologies such as tidal power, wave power and other novel options are still in their early research stage in China and we have to wait for at least 15 years or more for their commercialization.

On the demand side, there are some novel techniques to conserve primary energy and power in buildings as 'low carbon buildings' in the medium-and-long term perspective, but the most important near-term options are innovation in industrial processes to ease power demand in production. For options to save energy consumption in buildings, considering the low turnover rate of houses (a typical house will be used for at least 50 years) even there are available options for new housed as passive solar technique, simpler building refurbishment technique such as improved insulation and double or triple glazing will be the most cost-effective and easy to implement.

With regard to energy carriers and storage streams, fuel cell and hydrogen from various sources are still at the early research stage, promising but unavailable for large-scale application for at least 20 years. The current mature options as batteries and pump storages are energy-consuming for power storage and thus can only be used for small-scale or spare applications.

And finally we discuss the nuclear power stream. By the end of 2008, Chinese nuclear power capability in operation was 9 GW. China's mid-and-long-term Nuclear Power Development plan and its revision [62] suggests that by 2020, the operation capability will be 60–70 GW with 30 GW under construction, and the capability of nuclear power will be more than 5% of overall installed capacity. Currently there is widespread and hot debate on the future of nuclear power and Chinese government also temporarily suspends approval of new nuclear projects as a response to the serious nuclear accident in Japan [63]. As a result, China government will put more attention on hydropower, wind and solar power to meet the 15% clean energy goal in 2020. Nonetheless we argue that the underlying trend of nuclear power in China will not be radically changed, due to three reasons. First, China relies on nuclear power for 5% primary energy supply given the still small scale of non-hydro renewable; second, with the increasing international pressure to reduce carbon emissions, nuclear power is a "must" choice for China; and third many countries and regions have high nuclear shares over the generation mix, e.g., France (77%), Japan (33%), the US (20%) and European Union (35%), while China (2.1%) is far lower. Actually, in the National Energy Work Conference held in January 2011, the previous 40 GW goal for 2020 was revised as 80 GW (thus double the goal proposed in 2007). And the newly published 12th national economic and social development plan (FYP) outline (the topmost economic plan in China) at 16th March 2011 states nuclear power policy "*On the base of guaranteed security develop nuclear power efficiently* " and "*develop nuclear power in eastern coastal and some developed inland areas*" [64].

4. Pathways towards low carbon power system in China

4.1. Landscape prospect

China has experienced rapid economic growth for more than three decades. According to [46,48], per capita GDP in China grew at an accelerating rate, with the compounded annual growth at 7.7%, 9.25% and 9.38% for the last three decades. The Chinese government has proposed an economic growth goal in 2000 that per capita GDP will surpass 3000 US$ (2000 price). However because of the rapid growth in the past decade in 2010 per capita GDP already reached 2330 US$. Trying to describe the realistic picture, we thus choose a set of rates in linear decreasing trends and suppose them at 8.2%, 6.8%, 5.9% and 5.1% for the next consecutive five-year till 2030 (compound annual growth rate at 6.5%) to calculate the per capita GDP for landscape analysis. For demography, with the growth rate peaking during the 1980s, there is obvious trend to slow-down in the past two decades. Also, there is widespread discussion on China's population dynamics and the consensus is that population will peak around 2020 and will decrease slightly afterwards (Table 2).

Output structure will also exert significant impact on energy and power demand. Currently in the group of lower middle income, China's output is predominantly secondary industry (especially the manufacturing sector) and is lower in tertiary industry. However with the ongoing industrialization process, the share in the secondary industry will not decrease significantly until 2020, thus will pose a great challenge to China's energy supply and low carbon development.

According to the above analysis, the baseline socio-economic prospective is complied in Table 3. In the prospective, in 2015 when per capita GDP exceeds 3000 US$ China would step into the

Table 2
Historical key socio-economic series for China, 1971–2010.

	Year/period	Per capita GDP (2000 US$)	population (million)	GDP (billion 2000 US$)
History data	1971	127	841	107.1
	1980	186	981	182.9
	1985	290	1051	304.5
	1990	392	1135	444.6
	1995	658	1205	792.8
	2000	949	1263	1198.5
	2005	1451	1305	1893.4
	2006	1611	1312	2113.0
	2007	1809	1320	2387.7
	2010	2327	1340	3120.4
Growth rate (%)	71–80	3.53	1.411	4.98
	80–90	7.7	1.468	9.28
	90–2000	9.25	1.069	10.42
	20,000–10	9.38	0.604	10.04

Note: [46] for 1971–2007 data and [65] for 2008–2010 data.

Table 3
Key socio-economic variable baseline and BAU power demand scenario for landscape analysis in China.

Year	per capita GDP (2000 US$)	population (million)	GDP (billion 2000 US$)	Output structure (%)			Electricity demand (TW h)	Per capita electricity consumption (KW h/person)
				Primary	Secondary	Tertiary		
2010	2327	1340	3,120.4	10.2	46.8	43	4,056	3000
2015	3451	1390	4,797	10	46	44	5,628	4050
2020	4795	1450	6,952	9	45	46	7,503	5170
2025	6386	1420	9,069	9	42	49	9,514	6700
2030	8190	1400	11,465	8	40	52	11,091	7920

Table 4
Comparison of per-capita electricity consumption for different income group and countries [66].

Unit: KW h/person	1971	1980	1990	2000	2005
high income	4271	5,871	7,390	8,934	9,403
upper middle income	663	1,146	2,617	2,477	2,749
lower middle income	383	469	678	708	891
World	1198	1,583	2,121	2,389	2,673
United States	7517	9,862	11,713	13,670	13,692
Canada	9301	12,764	16,109	16,991	17,319
Japan	2531	2,950	3,546	4,080	4,061
Germany	4062	5,796	6,640	6,636	7,113
France	2812	4,527	6,127	7,485	7,944
United Kingdom	4252	4,684	5,357	6,115	6,252
Italy	1949	2,318	2,586	2,997	3,120
China	151	282	511	993	1,783

upper middle income group, and in 2030 when per capita GDP exceed 8000 US$ China would approach the floor level of high income group. Our prospective is largely in accordance with China Government's long-term vision of "build a well-off society in all-around way in 2020". Meanwhile the share of secondary will drop to 46% in 2015 and 40% in 2030, while the share of tertiary of will increase to 44% in 2015 and 52% in 2030. With per capita GDP approach 5000 US$ in 2020 and exceed 8000 US$ in 2030, considering the rapid growth in the past decades and the ongoing industrialization process, we assume that China's per capita electricity consumption will exceed 4000 kW h in 2015 (about the level of high income country group in 1970s), 5000 kW h in 2020 (approaching high income country level in 1980s) and approach 8000 kW h in 2030 (about the level of US in the 1970s and the high income country group in the middle of 1990s) (see Table 4). Accordingly, we compile a baseline power demand for analysis. Electricity demand would reach 7500 TW h in 2020 and 11,090 TW h in 2030.

When the size of the economy size more than triples and at an income level where consumption is bound to take off, what are the most important factors that exert pressure on China's power system regime? Here we will brief analyze four of them as industrialization, the built environment, electric appliances (household and commerce applications) and transportation.

The leading important factor is the industrialization process. During the past decade, the growth of energy-intensive products such as steel and cement etc. in China has been very fast. According to [67], China accounts for 70% of the increased production in crude steel, 83% in cement and 118% in steel material during 2000–2008, which implies that with the increasing pressures of energy and environment for the industrialized nations (especially the Annex I Kyoto Parties), more energy-intensive products are outsourced to China (Table 5). On the other hand, energy efficiency in China's manufacturing sector is significantly lower than developed countries, because of the laggard technology and the low value added. Because of international trade and the vast domestic demand, though the share of manufacturing sector in total GDP will decrease, heavy industry will experience significant growth and the absolute size of manufacturing sector will more than double in 2020 and triple in 2030 as of 2010, thereby resulting in vast growth of power demand and posing perhaps the biggest challenge to low carbon electricity transition in China. Therefore, a well-designed industry policy to guide the healthy development of the manufacturing sector, as well as strict energy efficiency standard to promote conservation will be among the most important options in China.

The second important factor is urbanization. Together with the increase of income, it will exert significant impact on the power system in two ways. First, urbanization is the aggregation of population in urban areas. The urbanization rate in China increased from 36.2% to 46% from 2000 to 2010 (implying 14 million citizens

Table 5
Comparison of selective energy-intensive products production in China and the world [67].

Units: 10 thousands tonnes	2000			2008			China share in the growth (%)
Selective energy-intensive product	China	World	China share (%)	China	World	China share (%)	
Crude steel	12,770	57,009	22.4	56,900	120,000	47	70
Steel materials	14,121	92,947	47	69,600	140,000	50	118
Cement	59,700	175,588	34	163,000	300,000	54	83
Sodium hudroxide	648	4,500	14.4	1,718	5,866	29.3	78
Calcined soda	803	3,460	23.2	1,553	4,800	32.4	56
Ethylene	479	9,000	5.3	2,431	12,040	20.2	64

moving into cities annually) and will increase to 56% in 2020 thus resulting in vast housing demand. China has set the goal of constructing new homes for 400 million people by 2017 ([17] p. 265). Houses are built for the long-term, on the expectation that houses will be used for 50–70 years or more. On one hand, house is a kind of stand-alone system implying that a new house could be built using the most modern and energy-efficient technologies (passive solar house for example) available without regard for how other houses in the surrounding area have been built. On the other hand once built in its life cycle, buildings will consume substantial amounts of energy for lighting, ventilation, cooling and heating purpose. It is reported that the energy consumption per square meter in the existing 40 billion square meters of housing in China is three times of that in advanced countries, while 90% of newly built houses are energy-inefficient. Hence to cope with the impact of urbanization and reduce the power demand in buildings, it makes sense to immediately implement as much available energy-efficient house technology as possible in the new construction projects. On the other hand, refurbishment of existing houses, by improved insulation, new heating systems such as heat pumps to replace central air-conditioning can improve energy efficiency remarkably.

Urbanization will also result in the expansion of cities, in turn result in increasing demand on regional transportation. The relationship between transportation and power sector is complicated. On the one hand, all kinds of biofuels could also be used for power generation. Considering the gigantic oil demand in the future, the inadequate domestic oil supply and the already high oil import dependence rate (50% in 2009), biofuel should take priority over bio-generation whenever possible. On the other hand, the technology of next generation vehicles, hydrogen/fuel cells or battery driven, will have significant impact on power sector. However, according to [68], hybrid electric vehicle technology may be the only one mature enough in the next 10 years. Pending significant improvements in battery technology, plug-in hybrids could possibly start making an impact in about 10 years, while vehicles powered by fuel cells are unlikely to enter high-volume production in less than 20 years. Whatever technology evolves, power demand will be significantly pushed up, by direct consumption by batteries or indirect consumption by hydrogen/fuel production. Considering the vast growth potential of private car demand [69], transportation alone will magically increase power demand in China.

With growing per capita GDP and more disposable income, electric appliances will be popularized in households. Comparing the difference of appliance inventories in rural and urban families [46], there is vast potential for demand growth for kinds of appliances such as refrigerators, washing machines, computers etc., which in turn will consume more electricity (Table 6). On the other hand, with the expected rapid growth of the service sector in the coming two decades, the popularization of office automation and more large scale power-consuming data centers put into operation in the future, there will be growth of power consumption by appliances in the service sector.

Table 6
Comparison of selective electric appliances in rural and urban families [46].

Units/100 households	Urban family		Rural family	
Year	2005	2009	2005	2009
Washing machine	95.5	96.1	40.2	53.1
Refrigerator	90.7	95.3	20.1	37.1
Air-conditioner	80.6	106.8	6.4	12.3
Color TV	134.8	135.6	84	108.9
Computer	41.5	65.7	2.1	7.4
Private car	3.4	10.9	–	–

4.2. Possible pathways

According to the above analysis, to break the carbon lock-in and ease the intensified international pressure in the future, the only feasible options for China are: (1) a more balanced economic growth plan, which calls for effective and practical development policies, especially policies for industrial sectors; (2) more energetic efforts on energy efficiency (technological innovation in manufacturing sector, improved energy efficiency in buildings, high energy efficient appliances, and comprehensive city, transportation and building planning) would be vital to avoid the potential future demand; (3) more penetration of clean energy sources in primary energy supply, especially more radical development of hydro, wind and solar power in the near future, (4) more joint research and development (R&D) and commercialization efforts with international partners to deliver CCS and carbon gasification technologies in the medium future, considering the unavoidable role of coal in China's energy system; and (5) more active science and technology research input in fusion nuclear and next generation hydrogen alternatives in the hope to replace the current hydrocarbon based energy source.

In this section, to explore a range of potential transitions associated with China's power system decarbonisation in a long-term perspective, we are determined to probe the overall canvas and will not constrain ourselves to technique or engineering details. Because of the endogenous uncertainty in system innovation process and the vast complexity of the topic itself, the picture is destined to be imperfect, harsh and speculative. A two-stage approach is employed in the study, with the first stage ranging 2010–2020 while the second 2020–2030 for convenience of analysis and also to approximately cater to the technological innovation stages. Then different technology options are classified into the reproduction, transformation, substitution, reconfiguration and de-alignment/re-alignment pathways according to their respective property in the transition process. Table 7 lists the possible options in every pathway for two stages Table 8.

For the first stage, the feasible pathways will focus on reproduction, transformation and substitution. In the reproduction pathway, considering the already high energy efficiency of coal power plants in China, the effect of regular efficiency enhancements in existing units would be tiny, but replacement of small-scale inefficient units

Table 7
Possible power system transition pathways in China.

Stage Pathway	First stage: 2010–2020	Second stage: 2020–2030 (and beyond)
Reproduction: efficiency enhancement in coal-based large-scale power system	Regular efficiency enhancement; CHP; substitution of small scale inefficient unit with UVC unit; power grid operation optimization	Same as first stage
Transformation: minor modifications to coal-based large-scale power system	Demand side options as technology innovation in industrial process, popularization of energy efficient appliances, house refurbishment such as insulation and double glazing; isolated distributed generation (DG) in remote areas	Low carbon building
Substitution: technology substitution or power demand substitution within centralized power system	Gas power, waste (biogas) power and/or gas+CHP; fission nuclear power; inland and onshore wind power; solar power in demonstration and commercialization; heat pump; passive solar	Gas+CHP power; GIF nuclear; offshore wind power; advanced solar power; fuel cells; MicroCHP
Reconfiguration: major modification to coal-based large-scale power system	CCS research and experiment and demonstration; Fuel cells research and experiment and demonstration; Centralized power grid+solar/wind/hydro/biogas and other combined DG	Regional power grid+ultra voltage transmission connection+expansion of kinds of DG technologies including fuel cells
De-alignment/re-alignment: power system coevolves with hydrogen/fuel cell technologies	Research and development of hydrogen technology	Possible Macrogird with large-scale UVC+CCS units and other traditional carbon-free units or large scale fuel cell plants based on underground coal gasification+hydrogen production as carriers+Possible DG and Microgrid with fuel cell, wind, solar and other units

Table 8
Comparison of two opposite policy fault-lines on innovation [33].

“Let market do it” fault-line view	Correct fault-line
Is undefined-all ‘innovation’ being good	An understanding of what ‘innovation’ is and that not all of it is ‘good’
Supports economically rational policies which complement large-scale, status quo companies rather than policies which encourage, create or reach multi-scale, multi-diverse unknown outcomes	An acceptance that markets are not the best way forward for making all choices-although certainly they are for many decisions (if not the majority) and will continue to be central to any future sustainable energy system
Believes in linear, predictable development or innovation (which enables a predictable known outcome from policies)	That it is not only acceptable to ‘pick’ a technology to support but necessary to ‘channel’ innovation policies
Considers quantitative economic as superior to broad qualitative analyses, not least because it finds the latter difficult to incorporate	That choosing to support an environmental potion, which may not be a least-cost measure, rather than choosing the economic or market option, may be appropriate, necessary and sensible and provide a great deal of additional value, albeit not in a way which is able to be valued monetarily
Considers broad carbon reduction policies superior to focused, technology policies because the latter have to ‘pick’ a set of technologies or a particular technology	Accepting that trying to meet the challenges of climate change is a ‘system’ issue not a technological-only issue
Consider risk as an important stimulator in innovation while policies which reduce risk, inevitably, soften competitiveness which in itself must be undermining to incentives which lead to the ‘right’ answer	The risk and transactional cost of innovation is directly affected by the policy, which should tries to reduce it to encourage entrance and learning-by-doing at reasonable input of the government

with UVC or CHP units is promising. In the transformation pathway, technology innovation in industrial process, popularization of energy efficient appliances, refurbishment of existing housing to increase energy efficiency, promotion of distributed generation in remote regions with alternative clean energy sources would be priorities. In the substitution pathway, developing safer fission nuclear power in eastern coastal regions, developing a large inland and onshore wind power base, large-scale CHP gas power in relatively developed eastern regions, small and medium scale waste (biogas) CHP generation to provide local grid would be priorities. Particularly, solar power could be promoted by employing even more policy incentives to breed another important alternative renewable in China as soon as possible. Heat pump and passive solar technology which can substitute power demand substantially in household and office building could also be promoted. During the first stage, though there will be no obvious progress in reconfiguration and de-alignment/re-alignment pathways, proper R&D input in related technology, especially CCS, coal gasification, hydrogen production, fuel cell, next generation nuclear power etc and investment in their demonstration and commercialization is very important. For such a tremendous work, hand-in-hand cooperation with international partners on selective promising technology is a priority.

For the second stage, with the increasing share of renewables in different scales and breakthroughs in next generation nuclear and energy carrier/storage technologies, a multi-layer power system, consisting of large centralized units such as UVC+large scale hydropower+nuclear+gas units interconnected by an ultra-high voltage DC/AC transmission system as the upper layer (macrogrid), thousands of regionalized medium scale renewables, CHP gas and/or biogas with fuel cells power as backup and other power storage facilities interconnected to macrogrid as the middle layer (mesogrid) and millions of localized small-and-medium renewables, microCHP with small scale fuel cells, interconnected with the regionalized Grid as the bottom layer would be gradually shaped. Hydrogen and fuel cell would serve as vital energy carrier/storage facilities in the system.

5. Policy design implications for transition management

5.1. Basic assumptions on policy design

In analyzing the failure of the UK government in promoting sustainable energy, [33, p. 12–13] highlights the importance of Regulatory State Paradigm and the related policies on innovation process, which is vital to sustainable energy transition. According to [33], the challenge of successfully achieving a transition to a sustainable energy system, rests on the ability of policy makers

(at all levels and in all positions) to encourage and enable the necessary changes or innovations at the energy system level, at a firm level, and also in the patterns of sustainable consumption and behaviors across society. However, the logic of market rests on cost-efficiency and may obstruct innovation when the price is uncompetitive. Government action should be focused on establishing a selection environment which is conductive to 'innovation' and to try to 'channel' the innovation as far as possible in the right 'direction'. Particularly 'not all innovation is good', in this situation Governments cannot 'leave' it to technology and fuel blind markets but do have to make a choice about what kind of energy future they want. Hence it is naturally that market approach alone is not enough and regulated approach is necessary. Ref. [17, p. 98] also argues that market economy is very efficient for the allocation of resources, but only in a slower evolution process. Also sometimes market is not perfect because of "path lock-in". On the other side, because of limited time and resources, we need to rapidly expand the use of existing energy-efficient technologies and products and develop a number of new alternatives, which is rightly the advantage of planning. Ref. [70] also argues that the energy transition for the U.S. needs a planned program similar to the American Apollo program that put a man on the Moon in 1969. Besides, [60] also argues for a federal program to stimulate innovation in energy technology in the U.S.

5.2. Policy design implications for China

In considering the policy fault-line for innovation, a natural question is how to manage the energy transition process. Therefore, a clear understanding of the innovation process is important. According to the standard pipeline model in innovation theory, a typical innovation process is as the follows: research that stems from the curiosity of scientist or inventiveness of engineer leads to an invention, which requires development to ready it for prototyping and then for commercialization. This model stresses the process of technology supply-push, in which new technologies evolve and push themselves into the marketplace. The major obstacle to innovation of this kind, namely the "valley of death" in the literature, is the gap in support and financing between basic research and later-stage development. As a result, the success of many major innovations has typically depended on a strong injection of public money enabling them to bridge this valley of death [60]. On the reverse side, according to market-pull model, most new products stem from the more mundane process of market or demand pull, during which a market opportunity gives rise to an innovation, which eventually creates requirements for the development and lastly for research. However, the innovators make these long-term investments on new technologies in research, development, and demonstration only when they are convinced that the new environment is here to stay, at least long enough for the resulting technologies to be preferred and come to the market. While these two theories address on the process by which innovation occurs and the external influences to which it responds, the third theory, innovation organization addresses the management of innovation and the organizations in which it takes place. Accordingly, organization mechanisms are needed to help bridge the gaps between public and private sectors and institutions are needed to help smooth the interaction between public, private and academic sectors. However, energy poses multiple challenges to the models in innovation in that the solution to energy transition is a vast and complex array on both the supply and demand sides while the powerful entrenched array of incumbents is resistant to change.

Regarding energy transition management, [17] proposes a four-step framework, in which analysis of the overall situation and possible solutions is the first step; in the second step a high-level map of the general direction of change, or strategy is formulated; then in the third step numbers of plans, varying on the stages of the different technologies, are developed based on the strategy; and finally is the managed change. Ref. [60] also proposes four-step framework for restricting energy revolution as: first, categorize the many and diverse technologies according to their varied launch paths; second, match launch paths to policy packages; third, identify the institutional gaps, and finally fill in the gap. In our viewpoint, the former is largely top-down while the latter is more bottom-up. Combining these two frameworks we propose an interactive framework for China's power sector transition management as shown in Fig. 6.

For the top-down line, a long-term vision for electricity in China will be drafted first to guide electricity planning [71,72]. The overall planning then in turn guides more practicable sector plans and detailed implementations, for example, renewable generation planning for the next three decades, smart grid planning and its stage by stage implementation, energy efficient building programs, etc. On the bottom-up line, proper policy packages need be designed to support the implementation of sector planning and programs. Whether the policy for a specific energy technology is in the front end support or back end incentive and regulations depends upon the scientific technology path appraisal based on the state-of-art technology and market development. It should also be noticed that these designed policy packages, will in turn change the resource availability, basic science advance and technology potential on one hand, landscape and regime for energy, industry policy etc on the other hand, which in turn will exert new pressure and opportunity for the shaping of long-term vision.

According to the innovation theory, 'front end support', including research and development (R&D), prototyping and demonstration (P&D), public–private partnerships (PPP), monetary prizes for innovators, support for technical education and training is vital for supply-push innovation, while 'back end support', economic incentives and regulatory requirements or mandates to encourage innovation is vital for market-pull innovation. The back end economic incentive includes tax incentives and credits, loan guarantees and low-cost loans, price guarantees, government procurement programs, new-product buy-down programs and general and technology-specific intellectual property policies. On the back end regulation side, policy package includes government standards as appliance standards, energy technology (efficiency) standards in the building and construction sectors, regulatory mandates, such as renewable portfolio standards for utilities, fuel standards, fuel efficiency standards and emission taxes, etc. For all kinds of technology, there is an important role for the government to implement transitional R&D to overcome "death valley" at different launch stages are necessary, on the other hand, there is also an substantial role for government supported R&D to facilitate the secondary and incremental innovations (or the technology learning) in the manufacturing process.

Though the purpose of the paper is not a case-by-case technology appraisal and policy recommendations as done in the previous work, here some technologies will be briefly discussed to demonstrate how to design policy packages according to the state and nature of the specific technology. Five representative technology/classifications are chosen in this section, namely large scale on-grid wind/solar, small off-grid wind/solar distributed generation, energy efficient building, CCS, and nuclear technologies.

As analyzed in the Current power landscape and niche in China section, from many perspectives, China has achieved great success in developing wind power from small scale off-grid niches gradually into the mainstream power regime. However, there are

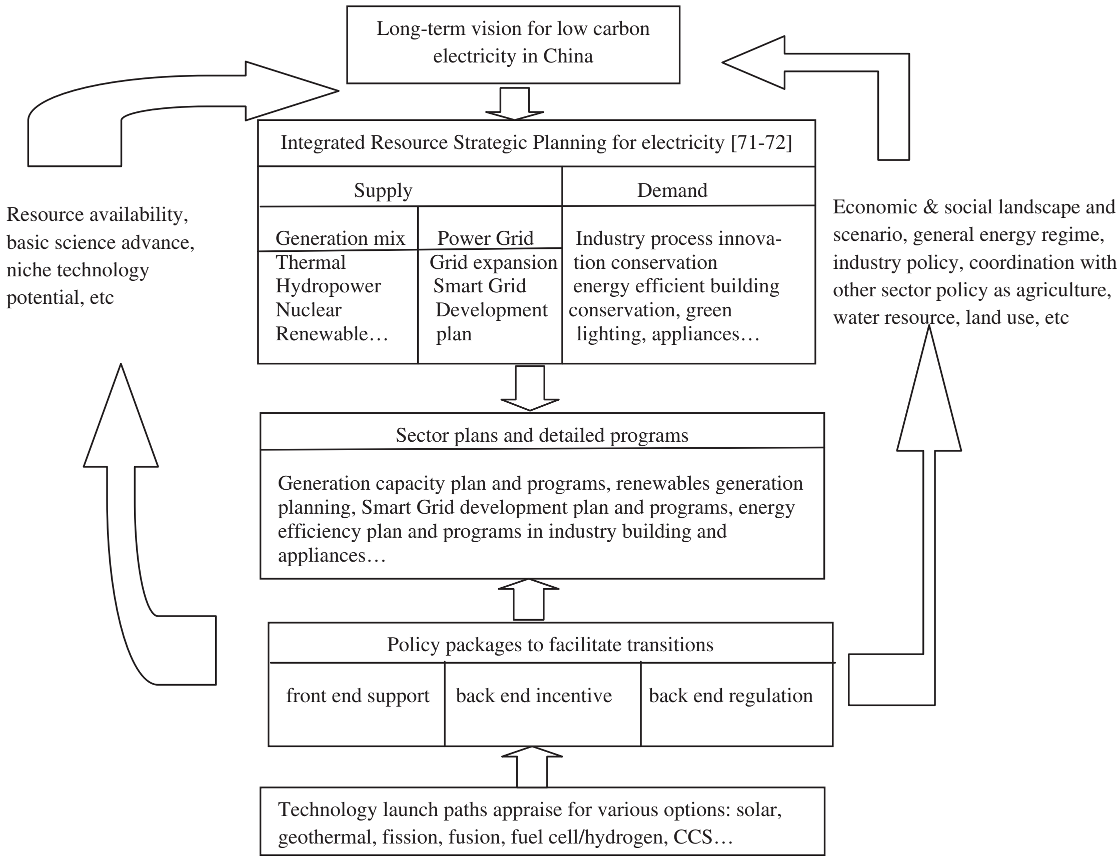


Fig. 6. An interactive management framework for Power transition in China.

many obstacles preventing the acceleration of wind power and deserving special attention for policy design. For solar power because of the still high cost (PV or CSP) the generators have not incentive to install solar capacity. On the other hand, without substantial learning-by-doing, the cost will not go down in the learning curve [73]. Because of solar is definitely the next most promising renewable technology and because low carbon transition needs an ecosystem rather than one ultimate technology [74, p. 246], more front end R&D and P&D support for solar is needed for its takeoff in China.

As argued before, to reduce supply cost as well as to develop renewable to the upper most, the optimum paths for renewable generation should include large-scale on-grid and small-scale off-grid generation. Considering the future reconfiguration scenario of numerous renewable units in different sizes and different technologies located almost everywhere, the government needs to work out the timetable and program for DG development. However, because of the potential competition with the two national grid operators, the strongest opposition may come from them. Therefore government needs to formulate electricity pricing reform to separate the current jumbled electricity price into generation, transmission, distribution and retail prices. On the other hand, in some isolated area with convenient condition (i.e., with plenty of hydropower resources to serve as the backup for renewables or with plenty of solar and wind resources simultaneously) may be chosen as experimentation and demonstration for DG technology. Besides, DG should best be invested in by numerous private investors to reduce the heavy financial burden on the large incumbents. Fair investment environment must be shaped to attract private investors.

Many energy efficient building technologies are mature in a commercialization sense, but their implementation in China is rare. Various sources have confirmed that buildings are a large energy consumer and carbon emitter and the current energy intensity in China's buildings can be cut by a factor of 1/2 to 2/3 and thus contributing a major proportion in energy conservation [75,76]. It is also worthwhile noticing that because of the low turnover of houses, retrofitting of old houses is at least same important as building more efficient new ones. Although improvement on this scale is a dramatic challenge, the energy conservation opportunities are legion: the current available options including high-efficient bulbs, daylighting and actively controlled window shading, highly insulated windows, pigments for roofing and walls with high reflectivity and emissivity to minimize heat gain, heat pump and many others; the newer approaches still need further R&D for passive systems including LEDs, windows with controllable optical and thermal properties, new material for building shells with superior structural and insulating properties and others. Adoption of these technologies will inevitably result in additional cost to builders and homeowners. Unfortunately, the building sector is notoriously slow to adopt innovations, while both builders and purchasers of real estate are notorious for preferring low initial cost to minimum life-cycle costs and thus for insisting on short payback periods on investment in conservation that raises initial prices but saves money in the long run. Demonstrations of energy-saving technologies at a scale invested in by government may assist in educating the market, including builders, service providers and consumers. New appliance and lighting standards that fit technology advances in these areas also require implementation. Lack of professionals is also a potential problem. Though energy service in many industrialized countries has developed into an expanding sector, their development in China is still immature. Creating incentives for the grid company, especially their urban

distribution affiliations to promote energy savings, instead of simply rewarding them for expanded power consumption, could promote the introduction. This will in turn call for the redefinition of the function of the grid company, especially the division of natural monopoly aspects as power transmission and distribution and system operation and dispatch, with the competitive aspects of power supply and energy services for reconfiguration of the power grid in the future. Then SERC could be empowered to push forward power market reform and implement more performance-based regulation on the natural monopoly sectors of the power system.

CCS is the leading mechanism offering the prospect of allowing continued use of coal while resolving coal's profound CO_2 emission problem. Considering the coal-dominated primary energy and generation structure, CCS is the most promising technology for China. Globally Europe and the U.S. are leading in CCS technology R&D. Currently there are about 100 CCS projects in operation globally while less than 10 of them are implemented at large scale (Mt annually). However none of these projects can provide an adequate level of assurance in storing very large quantities of CO_2 over the long term without significant risk of escape, especially given the scale of storage required: a 500 MW coal power plant will generate a billion barrels of liquefied CO_2 [77]. China's CCS technology research is initiated by Ministry of Science and Technology in 2007 and only three pilot projects are delivered in China. A viable CCS technology would consist of three stages: separating the CO_2 from utility and industry sources, transporting it to a storage site and isolating it from the atmosphere for hundreds of years until replacement alternatives evolve. Therefore CCS is still in its early research and demonstration stage and major challenges are: (1) cutting the cost of CO_2 capture, the current capture, transportation and storage process is estimated to increase the power generation cost by 50–100% in China; (2) establishing scientific certainty regarding the security of extremely long-term storage of CO_2 in a geological formation at the very large scale required; (3) developing the best practices for operating storage fields long term; (4) developing a (global and national) regulatory structure that would permit the introduction of CCS [78–80]. For large scale applications of CCS in China, more challenges could be added: (5) providing the needed sites of subterranean structures appropriate for long-term carbon storage; (6) building the vast infrastructure for CO_2 transportation; and (7) providing the gigantic investment to meet the project developing requirements (China and India together needing 1.17 trillion US$ into 2050 for capture facility alone [80]). Since CSS project is pure cost for developers before new and large-scale ways of commercialization application of CO_2 captured can be secured, the generators are unlikely to greet the huge cost imposition of CCS with enthusiasm. Similarly, since the CO_2 captured by CCS projects in one country is global public good at its own cost and without international legal framework, technology transfer and proper fund support from developed to developing countries like China are unlikely to promote CCS with enthusiasm. However, the current international arrangements are unable to provide such incentives. Assuming that such mechanism effective in the future, to promote CSS, on the front end, perhaps in an international cooperation framework, basic R&D on more efficient capture technology to reduce cost and increase energy efficiency, advanced subterranean structure siting and operation technology, advanced transportation technology and perhaps commercialization usage of CO_2 need to perform by direct government investment or PPP mechanism. Research is also required to describe, model, predict and monitor the path of injected CO_2 in various geological formations and the hydromechanical, chemical and biogeochemical processes involved. The earlier demonstration of CCS technology also needs government investment and possible PPP mechanism. At C&P stage, back end mandates such as low carbon energy supply quota, compulsive technology standards for coal plants, a global carbon market and carbon pricing mechanism etc is needed. Also, back end incentives such as government subsidies, PPP, tax credit and CDM mechanisms are needed to provide the necessary incentives.

Nuclear power has been actively researched and developed in China, although China is largely a late-comer in nuclear industry. The current most advanced nuclear technology, AP1000 was introduced in China in 2007 and the current units under construction are mostly third generation technology, which offers better fuel technology and passive safety so that the reactors shut down without operator intervention in case of an accident. In 2001 China also participates in the fourth generation (GIF) project, which promised to provide the next generation nuclear technology for sustainable energy generation, minimize the nuclear waste, offer life-cycle cost advantage over other energy sources and have more safety and reliability in operations [81]. Six next generation systems, including Sodium-cooled Fast Reactor (SFR), Very High Temperature Reactor (VHTR), Super-Critical Water-cooled Reactor (SCWR), Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR) and Molten Salt Reactor (MSR) are under R&D by GIF, among which VHTR could be used for hydrogen generation and thus could provide a promising position for nuclear power in the future hydrogen economy. Recognizing the recent serious accident in Japan, a more collaborative international partnerships to disseminate best practices on design, operation and disposal of radioactive waste is needed for global sustainable of nuclear. Realizing the fast growing of nuclear power in China on one side and shortage of proprietary intellectual property rights on nuclear technology on the other side, on the front end, China needs to advance R&D with more active participation with international partners, while on the back end, needs to promote P&D for new technology with PPP and tax credit incentives, provide favorable policy for investment in non-fossil energy, promote standardized design practices and domestic manufacturing by technology standard and favorable industry policy, and especially importantly, provide legal mandate for safety operation. (See Table 9 for a summarization of the analysis in this section.)

5.3. Potential institutional gaps for transitions

According to innovation organization theory, institution plays vital role for coping with "death valley" in the different stages of innovation. The following analysis also reveals that some institutional gaps should be filled for better delivering low carbon transition of China's power sector:

A government body to work out integrated energy strategy, sector plan and detailed programs. Considering the complexity of transition, the current energy institution framework on central government level is deficient and a well-functioning legal framework for electricity sector jurisdiction and decision-making is needed [31]. At least, before a ministry in charge of energy strategy and policy can be set up, the National Energy Administration resided with State Development and Reform Commission should be authorized to work out comprehensive energy and power planning.

Gradual redefinition on the functions of the grid company and possible reformation according to the transition process. Grid company plays vital role in the power system transition. Integration of renewable generation in large scales requires the related T&D system expansion and investment, revised dispatch rules as well as advanced operation technology; DG with various kinds of renewable technology requires the possible reconfiguration of the currently centralized power systems into multi-level counterparts; the various customer side conservation options require

Table 9
Policy packages for power system transition and illustrations.

Technology launch path	Research and development	Prototyping and demonstration	Investment and engineering	Commercialization and popularization	Large scale delivering
Policy type/representative technology analysis	macro-policies, carbon charge, resource tax, level playing field policy in both technology and investor sense				
	Consistent policy overview, transitional and technology learning R&D support				
	Front end		Back end		
	National basic research activity; technical education and training;	P&D by government fund; PPP; SOE direct investment	PPP; Loan guarantee and low cost loan; Tax credit	**Incentive policy** **Demand side technologies**: customer education/information; purchase subsidy; new-product buy down program **Supply side technologies**: price guarantee; government procurement; intellectual property policies; grid investment and cost allocation policy for renewable in-access **Mandate**: government standards as appliance standards, energy technology (efficiency) standards; regulatory mandates as renewable portfolio standard, SOE direct investment, fuel standards, fuel efficiency standards and emission taxes	
Large scale wind/ solar project	**R&D support**: large capacity and efficient wind turbine; wind technology at low wind speed; breakthrough in blade material; breakthrough in CSP and other advanced solar technology **P&D support**: demonstration of new technology I&E support: policy supporting domestic manufacturing; PPP in technology transfer; low cost loan or tax credit for renewable manufacturers **C&P support**: integration plan of generation mix and power grid; renewable generation portfolio requirement for generators; grid-access requirement of grid operators; T&D system investment incentive for grid operator and cost allocation policy; favorable dispatch policy for renewable; Feed-in price based on learning curve				
Small scale wind/solar distributed generation projects	**P&D support**: demonstration for DG **C&P support**: regulatory mandates and technology standards for DG; clear generation, transmission, distribution and retail pricing mechanism; fair investment environment encouraging small investors				
Energy efficient building	**R&D support**: transitional R&D on energy efficient building; training of professionals **P&D support**: demonstration of new energy efficient building technology **C&P support**: building code; appliance and lighting technology standard; new product price buy down policy; subsidy for house-owner to house retrofitting; requirement on grid operators to provide energy management services				
CCS	**R&D support**: basic R&D on CCS technology; transitional R&D to decrease cost **P&D support**: demonstration of promising CCS technology in power plant; direct SOE incumbent generators investment **C&P support**: global carbon pricing mechanism; technology and fund support from developed to developing countries; compulsory technology standard; low carbon energy supply quota; tax credit and low cost loan; CDM mechanism				
Nuclear power	**R&D support**: basic R&D on GIF nuclear and fusion technology **P&D support**: demonstration of proved new nuclear technology; direct SOE incumbent generators investment; **C&P support**: favorable investment policy for none-fossil energy; domestic manufacturing policy; standardized design practice; legal mandate for safety operation				

redefinition on the role of utilities as a energy service provider instead the current power supplier. At appropriate timing, disassembly of the current national grid company into National Transmission Company, National System Operator (both physical infrastructure and market) and Provincial Distribution Company is necessary to facilitate the transition. However, providing the proper incentive to the incumbents without distorting the transition is proven difficult and currently there is no silver bullet even considering the worldwide power deregulation experiences.

An energy R&D body as well as industry-government consortia to provide integrated translation research and strong front-end support. Given the need for energy technology breakthroughs in the future, organized basic R&D as well as transitional innovation process to translate science breakthroughs into technology development is vital for crossing the ‘‘valley of death’’ in the innovation process. The capability of organizing the best university researchers with outstanding firms on technology R&D collaboration is the key function of this body.

A public corporation to provide Demonstration and Engineering and manufacturing process innovation financing support. In addition to translational R&D, there is a need for demonstrations of engineering-intensive technologies that commercial sector has no strong incentive to carry out on its own. Government cost sharing can be appropriate for the demonstration of new technology that works well at laboratory and pilot scales but requires expensive and risky demonstration at full scale. Demonstration assumed by private sectors with a cost sharing for such projects can help ensure private-sector discipline and a private-sector stake in the demonstration. Also, most new energy technologies must compete on price more or less from the beginning. It is thus essential to speed the expansion of manufacturing capacity in order to take advantage of economies of scale and lower unit costs. Therefore, a public corporation with private sector expertise and operating in an environment comparable to that of a commercial firm can be a mechanism to sponsor the demonstration and manufacturing promotion program.

A roadmapping thinktank to develop and update innovation roadmap. A coordinated effort between the public and private sectors can optimize the government’s role in identifying and addressing the most promising opportunities to overcome market failure. Thus a thinktank that could combine industrial, government and academic expertise to assess technologies, identify areas of needed precompetitive research and likely launch obstacles and then recommend appropriate policies and incentives to

facilitate deployment is needed for the transition. Especially in China, without unified ministry in charge of energy issue, the thinktank could serve as a policy and technology development coordination mechanism of the initiatives and programs sponsored by different ministries.

6. Concluding remarks

Recognizing the urgency and magnitude of low carbon transition in China, this paper employs the recent progress in multi-perspective socio-technical transition theory to study China's power sector. The paper has set out the theoretical and methodological basis for the specification of outline transition pathways to a low carbon power system in China. This has been exemplified by a brief discussion of the current power landscape, regime and technology niches, and the pressures on the regime from macroscopic social-economic transition during the accelerated industrialization, urbanization and modernization process, and the possible transition pathways. By incorporating the viewpoints of innovation theory, we also propose an interactive transition management framework consisting of a top-down line as vision guidance, integrated planning formulation and sector planning and detailed program implementation, a bottom-up line as policy package design based on case-by-case technology launch path appraisal to support sector planning and program implementation, and a central role on the policy package design due to its feedback effect on macroscopic landscape variables and then into the long-term vision. We argue that our approach both contributes to theoretical and methodological debates on specifying transition pathways, and will be useful in informing policy-makers and other stakeholders. The theoretical contribution relates to the integration of recent ideas on transition process into an integrated multi-level perspective of landscape, regime and niches. We argue that this will provide a richer analytical basis for the development of transition pathways than was the case for previous work on socio-technical scenarios. The policy-relevant contribution relates to the integration of innovation theory into the specification and management of these pathways and the institution capability build to fill the gaps. We argue that this will go beyond much recent work on China energy scenarios that have largely focused on technically plausible futures.

Regarding China's power sector transition to a low carbon future, the following points are extracted to conclude the paper:

- A clear energy development strategy and scenario is needed for guiding the power sector development.
- Integrated planning, covering both generation and grid infrastructure, considering not only physical power plant but also "efficiency power plant" from demand-side into should be drafted to guide low-level power development plans and programs.
- Looking into 2020, the most promising pathways are transformation including mostly demand-side options, substitution pathways including current mature or would-be mature options as wind, solar, gas and nuclear power, and reproduction pathways including CHP and UVC to increase energy efficiency; looking into 2030 and beyond, more options as GIF nuclear, numerous DG technologies and fuel cells etc will add to the substitution list and will begin to gradually reconfigure the landscape of the power system into complicated multi-nesting structures (and hence guiding the direction of power grid development).
- Strong power grid infrastructure is needed to deliver the low carbon transition. In the future the power grid should be able to assume the following functions in China: optimize the primary energy supply structure and facilitate the grid access of large-scale clean generation, and thus reconfiguration of distribution system and intelligent distributed generation technology are needed; serve as an alternative system besides railway and road systems for large-scale energy transportation and thus higher voltage transmission system with longer transmission radius will be needed; promote energy conservation on power demand side and also on generation and transmission sides and thus more consumer choices, customized power services and smart energy management will be needed. All these functions call for the power grid technology innovations in both hardware and software fields.

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